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Cost Optimization of Wind Turbines for Large-Scale Offshore Wind Farms

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Abstract

This report contains a preliminary investigation of site specific design of off-shore wind turbines for a large off-shore wind farm project at Rødsand that is currently being proposed by ELKRAFT/SEAS. The results were found using a design tool for wind turbines that involve numerical optimization and aeroelastic calculations of response. The wind climate was modeled in detail and a cost function was used to estimate costs from manufacture and installation. Cost of energy is higher for off-shore installations. A comparison of an off-shore wind farm site with a typical stand alone on-shore site showed an increase of the annual production of 28% due to the difference in wind climate. Extreme loads and blade fatigue loads were nearly identical, however, fatigue loads on other main components increased significantly. Optimizations were carried out to find the optimum overall off-shore wind turbine design. A wind turbine for the off-shore wind farm should be different compared with a stand-alone on-shore wind turbine. The overall design changed were increased swept area and rated power combined with reduced rotor speed and tower height. Cost was reduced by 12% for the final 5D/14D off-shore wind turbine from 0.306 DKr/kWh to 0.270 DKr/kWh. These figures include capital costs from manufacture and installation but not on-going costs from maintenance. These results make off-shore wind farms more competitive and comparable to the reference on-shore stand-alone wind turbine. A corresponding reduction of cost of energy could not be found for the stand alone on-shore wind turbine. Furthermore the fatigue loads on wind turbines in on-shore wind farms will increase and cost of energy will increase in favor of off-shore wind farms.

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Contents

1 Introduction

This report presents the results of site-specific design optimizations of wind turbines for a large-scale off-shore wind farm project that is being proposed by ELKRAFT/SEAS. The report was carried out as a part of the European Joule III project, "Cost optimising of large-scale off-shore wind farms", coordinated by ELKRAFT/SEAS.

This study was intended as a preliminary investigation of the relevance of site-specific design, including only overall design parameters, whereas a more complete study should be carried out at a later stage in the project. The basis for the optimization results is the planned wind farm at Rødsand in the southern part of Denmark and the results are established for part one (of four) of this planned wind farm. Part one of the wind farm contains approximately 100 wind turbines, each of about 1.5 MW of rated power.

The objective of the optimizations is to clarify the benefits of site specific design for off-shore wind turbines and to identify possible differences in the wind turbine design for off-shore wind turbines compared with on-shore wind turbines. The results are intended to be general design guidelines for the next generation of large off-shore wind turbines.

The results are based on the most recent developed design tools for wind turbines involving numerical optimization, Fuglsang and Thomsen, 1998. Detailed knowledge of off-shore wind farm effects are used, Frandsen et al., 1996. An important part of this method is time domain aeroelastic calculations of response that is used to establish detailed information on the design loads. The design method is briefly described in Chapter 2.

For the actual planned wind farm it is necessary to take two special operational conditions into account while specifying the design loads. First, the wind farm is to be installed at sea in an off-shore environment, where the ambient turbulence is different from on-shore locations. Secondly, the influence of operation in the wake of upstream wind turbines must be taken into account. The most important design loads have to be identified and on basis of this a cost function for the entire wind turbine must be developed. The cost function includes costs from manufacture and installation and is used to calculate the cost of energy which is the optimization objective. The load cases and the objective function are described in Chapter 3.

In Chapter 4, comparisons are carried out between design loads for a stand alone on-shore wind turbine at normal flat terrain and an off-shore wind turbine in a wind farm. The results of the optimization of a wind turbine for the off-shore wind farm are presented. A sensitivity analysis reveals the relative importance of the design variables and the conditions for the optimization. Finally, an optimization with the actual preliminary wind farm layout at Rødsand is carried out.

Chapter 5 contains a summarizing conclusion.

2 Description of the methods

The design tool is based on the combination of a numerical optimization algorithm with different basic calculation tools through an interface as sketched in Figure 2-1.

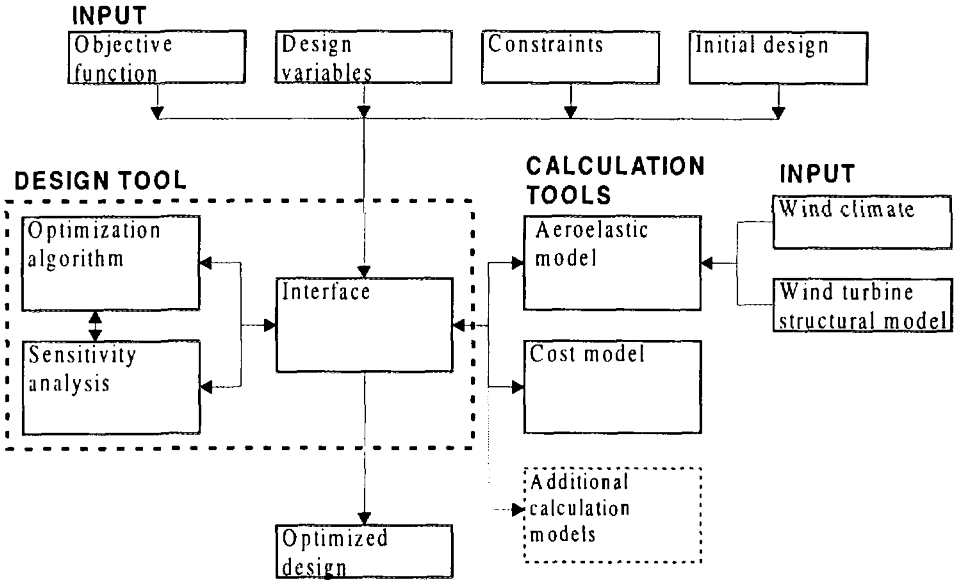

Figure 2-1 Overview of the design tool with necessary input and the coupling of an optimization algorithm with basic calculation tools through an interface.

The input to the problem is divided into the information which is required to execute the numerical optimization algorithm and the specifications for the basic calculation tools.

The numerical optimization algorithm needs:

- An objective function: The cost of energy, that has to be minimized by changing the design variables.
- A set of design variables: Any parameter that influences cost of energy such as rotor shape, wind turbine overall design and control parameters.
- Constraints: Upper or lower values for the design variables, but also limits on loads, stresses and strains, rated power or any calculable response parameter that is dependent on the design variables. The constraints bound the design space into a feasible domain in which the optimum is found.
- Finally, an arbitrary initial guess on a design vector is needed.

The specifications for the basic calculation tools involve:

- The wind climate, that is specified as the oncoming mean velocity profile, eventually modified because of wake operation or terrain roughness and the 3D turbulence field from the characteristics of the site.
- A complete description of the wind turbine aerodynamics, structure, control and safety strategies, so that the response of the structure to the wind inflow can be calculated and relevant fatigue and extreme loads can be derived.

When the design tool is applied, different basic calculation tools are used:

- Traditional aerodynamic analysis based on ordinary blade element/momentum theory is used for calculation of the power curve and mean loads.
- State-of-the-art aeroelastic calculations together with Rainflow counting provide fatigue loads.
- Extreme loads are determined from response time series and from a Davenport type model (Dansk Ingeniørforening, 1992).
- A cost model is used to determine the cost of each of the main components related to the design load cases. The cost of energy is then found from the annual energy production and the cost function that includes costs from manufacture and installation.

The aeroelastic model used in the design tool was the code, FLEX4, which was developed by Øye, 1992. It is a time integration aeroelastic model. It uses a relatively limited number of degrees of freedom (DOF) to describe the rigid body motions and elastic deformations of a wind turbine. In case of a three bladed wind turbine the number of DOF's is limited to 20. These degrees of freedom are two tower deflections, tower torsion and tower top tilt deflection. The shaft is described by two bending DOF's and a torsion DOF. Each blade is described by the first two mode shapes in the edge- and flapwise directions. The mean wind field over the rotor plane includes wind shear, yaw error and tower shadow. The turbulent part of the wind is included in the model as time series of simulated turbulence in a large number of points over the rotor disc, a method described by Veers, 1988, which includes a three-dimensional turbulence simulation.

The execution of the different calculation tools is controlled by the interface, that is tailored for communication between the numerical optimization algorithm and the calculation models. It generates the wind turbine configuration from the design variables. When the calculation tools have been executed, the interface evaluates the objective function and the constraints and necessary sensitivity information for use by the optimization algorithm.

The methods are described in more detail in Fuglsang and Thomsen, 1998 and in Fuglsang and Madsen, 1996.

3 Specifications for the design optimizations

Design optimizations were carried out for two different off-shore wind farm layouts and for an on-shore stand-alone wind turbine. Comparisons between on-shore and off-shore were carried out for the optimized wind turbine design, annual energy production, design loads and cost of energy.

The specifications for the optimization study include: A description of the 1.5 MW wind turbine that was used as reference, the wind resources for the on-shore stand-alone site and for the two off-shore wind farms (see section 3.2), the wind farm layouts for the wind farms including the distribution of free and wake flow, the load cases and the operational conditions, the cost function, the design variables and the constraints.

3.1 Reference wind turbine

The reference wind turbine is a 1.5 MW stall regulated wind turbine with a stiff upwind rotor corresponding to a typical Danish wind turbine. The main dimensions are shown in Table 3-1. The LM 29.2 blade is based on NACA airfoils and has a root chord of approximately 3 m. The structural characteristics of the reference turbine were modeled as a state-of-the-art Danish wind turbine.

Table 3-1 Reference wind turbine main dimensions

Rotor diameter (m)	60.0
Hub height (m)	59.5
Rotor speed (rpm)	19.8
Rated power (MW)	1.5
Regulation	Stall
Blades	LM 29.2

3.2 Wind farm layout

Two different wind farm wake conditions were considered:

1. The 5D/5D layout: A simplified wind farm layout with 5 rotor diameters (5 D) distance between the turbines and 5 D between the rows.
2. The 5D/14D layout: The actual wind farm layout where the distance between the wind turbines in the rows is 350 m and the distance between the rows is 850 m.

The layout of the wind farms are illustrated in Figure 3-1. A wind turbine in the middle of the wind farm was selected for the optimization. For some of the optimizations the rotor diameter was a design variable and for simplicity the distance between turbines was given relative to the rotor diameter, D. This implies that if the rotor diameter increased during the optimizations the absolute distance between the turbines increased.

The 5D/5D wind farm configuration was considered initially whereas the 5D/14D wind farm was used only in the final optimization.

Based on results from Frandsen *et al.*, 1996, only wake effects from the nearest turbines were considered.

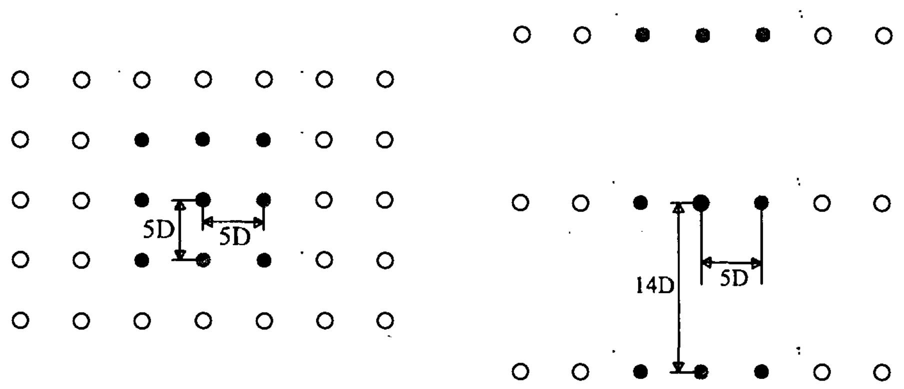

Figure 3-1 Wind farm layout. To the left the 5D/5D layout: a simplified wind farm layout with spacing between turbines and spacing between rows on 5 rotor diameters. To the right the 5D/14D actual wind farm layout with 5D spacing between the turbines and 14 D spacing between the rows.

3.3 The wind resources

The wind resources were estimated at 55 m height for three different wind climates:

1. An on-shore normal flat terrain in the Danish roughness class 1 with Weibull scale parameter, A = 8.08, and Weibull shape parameter, k = 1.9, with a uniform wind direction distribution.
2. The 5D/5D off-shore wind farm in the Danish roughness class 0 with Weibull scale parameter, A = 9.55, and Weibull shape parameter, k = 1.9, with a uniform wind direction distribution.
3. The 5D/14D off-shore wind farm at Rødsand with the actual wind direction distribution. The wind resources at the planned site was estimated on basis of long term measurements at Gedser land mast, Lange, 1997. The direction dependent wind resource estimates at Rødsand are given in Table 3-2.

Table 3-2 Estimated direction dependent wind resource at Rødsand (55m). From (Lange, 1997)

Wind direction sector	Wind direction probabilities (%)	Weibull A parameters (m/s)	Weibull k
0	5.68	8.03	2.06
30	2.69	7.89	1.75
60	2.79	7.20	1.73
90	10.50	12.60	2.37
120	10.42	9.89	2.49
150	6.42	9.01	2.51
180	5.94	9.10	2.56
210	9.86	10.54	2.33
240	13.29	11.17	2.40
270	17.17	11.53	2.49
300	9.18	8.92	2.24
330	6.06	9.00	2.26
Totals:	**100**	**10.21**	**2.35**

3.4 Free flow and wake operation

For some wind directions a wind turbine in the middle of the wind farm will be operating in near wake (5D), eventually far wake (14D) and for other directions in free flow. Using methods described in Thomsen, 1997 and Frandsen *et al.*, 1996, the number of operational hours in each of these three situations was calculated for the 5D/5D wind farm with a uniform wind direction distribution, Table 3-3 and for the 5D/14D wind farm, Table 3-4. The number of operational hours for the 5D/14D wind farm was obtained using the wind direction distribution in Table 3-2. A life time of 20 years was assumed in both cases.

Table 3-3 Number of operational hours in different wind inflow conditions for the 5D/5D wind farm with a uniform wind direction distribution. Total lifetime was 20 years.

Wind speed (m/s)	Free flow (hours)	5D wake (hours)
4	18031	15501
6	18834	12906
8	16868	9942
10	13389	7166
12	9580	4869
14	6240	3091
16	3724	1813
18	2046	984
20	1038	493
22	487	228
24	129	60
Totals:	**90366**	**57053**

Table 3-4 Number of operational hours in different wind inflow conditions for the 5D/14D wind farm with the wind direction distribution from Table 3-2. Total lifetime was 20 years.

Wind speed (m/s)	Free flow (hours)	5D wake (hours)	14 D wake (hours)
4	11072	1806	8194
6	15122	2498	11675
8	15835	2568	13469
10	13429	2069	13223
12	9443	1331	11253
14	5599	688	8367
16	2851	288	5456
18	1277	98	3129
20	517	28	1584
22	194	7	711
24	69	1	286
Totals:	**75409**	**11382**	**77346**

The main load generating wind parameter for wind turbines in wake operation is the turbulence intensity of the longitudinal wind component. This parameter was calculated for the three different inflow conditions using methods described in (Thomsen, 1997). The design turbulence intensities are given in Table 3-5.

Table 3-5 Design turbulence intensities for free flow and near wake flow (5D) and far wake flow (14D).

Wind Speed (m/s)	Free flow turbulence intensity (%)	5 D wake flow turbulence intensity (%)	14 D wake flow turbulence intensity (%)
4	0.068	0.228	0.103
6	0.072	0.212	0.101
8	0.076	0.196	0.100
10	0.079	0.184	0.099
12	0.082	0.175	0.099
14	0.085	0.168	0.100
16	0.087	0.162	0.100
18	0.089	0.157	0.100
20	0.091	0.154	0.101
22	0.093	0.151	0.102
24	0.095	0.148	0.103

3.5 Load cases and operational conditions

The wind inflow to the off-shore turbine consisted of part time free wind inflow and part time far or near wake inflow. These situations were considered separately and afterwards included in the total life time load spectrum using the probability of the free flow/wake operation, represented by the duration given in Table 3-3 and Table 3-4. The wake operation load cases were only

considered for the fatigue analysis since the extreme loads on a turbine usually occurs during high wind speeds where the turbine is shut down.
Loads during normal operation, i.e., during power production between the cut-in and the cut-out wind speeds, were included in the fatigue design load basis. Furthermore, a fault condition - error in yawing mechanism - was included and described as extreme yaw error, assumed to be ±30°, combined with cut-out wind speed, 25 m/s. Recent investigations illustrate the importance of this load situation, Thomsen *et al.*, 1997.

Usually start and stop situations are included in the design basis for wind turbines. However, for this particular optimization it was assumed that these situations would not contribute significantly to changes in the design loads for the considered components and thus these situations were not included.

The total number of operational conditions was 13 for each inflow condition. For the wind turbine in a wind farm the inflow condition was a combination of free inflow and wake inflow and the resulting number of operational conditions was either 26 or 39 depending on whether both near (5D) and far (14D) flow was considered.

3.6 Cost function

The cost function total cost, C, was calculated as a sum of contributions from the different wind turbine main components. The estimation of actual cost is difficult, since the pricing of each component depends on sub contractors and market economy. Therefore cost analysis was based on the estimation of component weight. For each component, changes in the design loads were converted to changes in characteristic main dimensions from allowable ultimate and fatigue stresses and strains. The component weight, m_i, was then estimated for each main component, i, from the characteristic dimensions.

The percentage cost distribution on the different main components was estimated for the reference rotor for installation at an on-shore site and at an off-shore site respectively, Figure 3-2. The total relative cost was 42% higher for the off-shore site because of increased foundation and grid connection costs, Svenson, 1997.

Each component cost, C_i, was split into a fixed cost share, b_i, and a variable cost share, $(1-b_i)$, $b_i \in [0;1]$. The fixed cost share represents for example manufacture and transport. The variable part depends on the component weight, Table 3-6. It was not considered to include different costs shares for on-shore and off-shore wind turbines respectively.

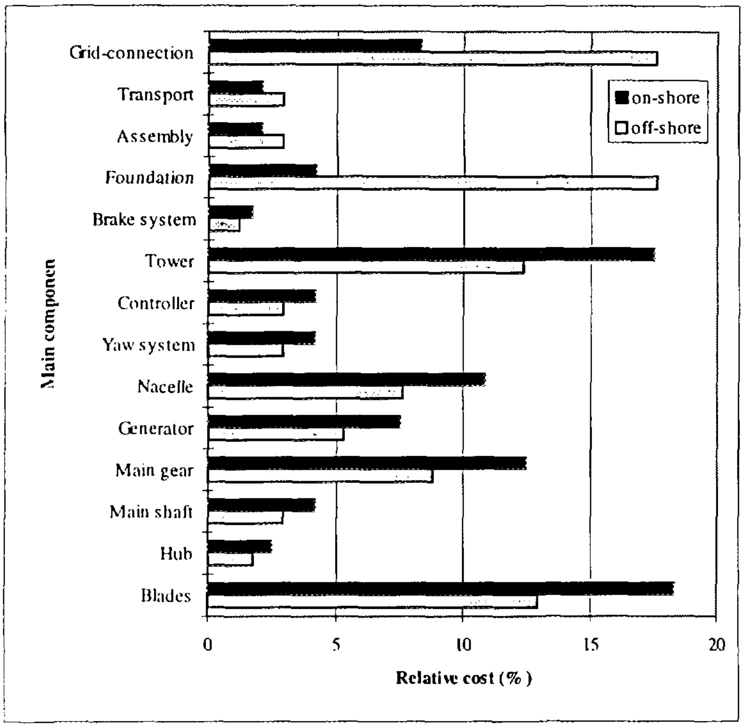

Figure 3-2 Distribution of relative cost, R, for main components for an on-shore wind turbine and for an off-shore wind turbine, Madsen et al., 1995 and Svenson, 1997.

Table 3-6 Relative cost share, R, and cost function for the different main components for an on-shore and an off-shore wind turbine, Madsen et al., 1995 and Svenson, 1997.

Component	Relative cost, R_i on-shore	Relative cost, R_i off-shore	Cost function, C_i
Blades	18.3	12.9	$0.1 + 0.9 \cdot m$
Hub	2.5	1.8	1
Main shaft	4.2	2.9	$0.3 + 0.7 \cdot m$
Main gear	12.5	8.8	m
Generator	7.5	5.3	m
Nacelle	10.8	7.6	$0.4 + 0.6 \cdot \mathrm{m}$
Yaw system	4.2	2.9	m
Controller	4.2	2.9	1
Tower	17.5	12.4	$0.3 + 0.7 \cdot m$
Brake system	1.7	1.2	m
Foundation	4.2	17.6	$0.75 + 0.25 \cdot m$
Assembly	2.1	2.9	1
Transport	2.1	2.9	1
Grid-connection	8.3	17.6	1
Total	**100**	**100**	

The total weighted percentage cost, C, was then found from a cost function for each main component:

$$C = \sum_{i=1}^{N_{COM}} C_i, \qquad C_i = R_i\left(b_i + (1 - b_i)\cdot m_i\right) \qquad (1)$$

Where R_i is the percentage cost for the i'th component, with the total relative cost, $R = \sum R_i = 100\%$, N_{com} is the number of main components.

We calculated the material consumption for each main component on a relative basis compared with the reference rotor on basis of the design loads in Table 3-7. The m functions were based on Madsen et al., 1995 and Svenson, 1997. Eqn. (1) was then used to find the relative percentage change in the cost function. The cost function was then compared for two wind turbines of equal concept. Since the variation of C_i with m_i is linear, only minor variations in the design loads and hence the characteristic dimensions should be allowed.

Table 3-7 Design loads.

Design load	U extreme load f fatigue load
Blade root flapwise bending moment	M^u_{flap}, M^f_{flap}
Blade root edgewise bending moment	M^u_{edge}, M^f_{edge}
Rotor yaw bending moment	M^u_{yaw}, M^f_{yaw}
Rotor tilt bending moment	M^u_{tilt}, M^f_{tilt}
Rotor thrust force	F^u_{thrust}, F^f_{thrust}
Tower base bending moment	$M^u_{towerbase}$, $M^f_{towerbase}$

The cost of energy, *COE*, on an annual basis was found relative to the reference rotor from:

$$COE = \frac{R \cdot C}{a \cdot E} \qquad (2)$$

Where C is the manufacture and installation costs, a is the annuity factor. On basis of Table 3-8, a = 12.46. E is the annual energy production. R is the total relative cost. On-going costs such as maintenance and losses in energy production from availability below 100% were neglected. The total manufacture and installation costs for the reference wind turbine was set to 17.6 million DKr for an off-shore installation and 12.4 million DKr for an on-shore installation, Svenson, 1997.

Table 3-8 Economic assumptions.

Economic parameters	
Interest rate, r, (% p.a.)	5
Life time of turbine, L, (years)	20

3.7 Design variables and constraints

Table 3-9 shows the design variables and the constraints. To limit the complexity of the optimization, the blade shape was kept fixed. The rotor diameter was changed by extending the hub section. This is not valid at very large rotor diameters where an entire new blade should be designed. The rated power depend on all design variables including the tip pitch angle that should be adjusted to control peak power. When the rotor diameter was changed, the distance between turbines were increased relative to the rotor diameter.

Constraints were applied to the design variables to limit the design space to reasonable designs within the validity of the cost of energy calculation, Table 3-9.

Table 3-9 Design variables and minimum and maximum constraints

Design variable:	Minimum	Maximum
Hub height (m)	50	70
Rotor speed (rpm)	15	23
Rotor diameter (m)	60	75
Rated power (MW) (Tip pitch angle)	1.5	2.0

4 Results

First, the design loads were calculated for the reference wind turbine in the normal flat terrain on-shore stand-alone site and in the 5D/5D off-shore wind farm site to investigate the change in loads for the differences in the wind climate and for the wind farm operation. Next, the reference wind turbine was optimized for both sites and design variables and main results were compared with the reference wind turbine at the respective sites. A sensitivity study was carried out to investigate the importance of the design variables and the sensitivity of the optimization results to some of the assumptions. Finally, an optimization was carried out for the 5D/14D off-shore wind farm.

4.1 Design loads for the on-shore and 5D/5D off-shore sites

Table 4-1 shows the cost identifiers for the reference wind turbine at the on-shore site and in the 5D/5D wind farm respectively. The cost identifiers influence the cost of energy and they were fatigue and extreme design loads, the annual energy production and nominal torque and power. The percentage differences for the 5D/5D off-shore site relative to the stand alone on-shore site are shown in Figure 4-1. The assumptions for the wind fields (wind speeds and turbulence) are given in Table 3-3 and Table 3-5.

Table 4-1 Fatigue, nominal and extreme design loads and annual energy production for the reference on-shore stand alone wind turbine and for 5D/5D off-shore wind farm.

	Stand alone on-shore wind turbine	5D/5D off-shore Wind farm
Fatigue loads:		
Blade root flapwise bending moment (kNm)	990	1015
Rotor shaft yaw moment (kNm)	819	1024
Rotor shaft tilt moment (kNm)	900	1139
Rotor shaft axial force (kN)	57.0	72.9
Tower base moment (MNm)	3.71	4.85
Nominal loads:		
Nominal torque (kNm)	801	800
Nominal power (MW)	1.50	1.49
Extreme loads:		
Blade root flapwise bending moment (kNm)	2.83	2.90
Rotor shaft yaw moment (MNm)	1.77	1.82
Rotor shaft tilt moment (MNm)	2.69	2.76
Rotor shaft axial force (MN)	0.50	0.52
Tower base axial force (MN)	41.5	43.0
Annual energy production (GWh)	3.66	4.68

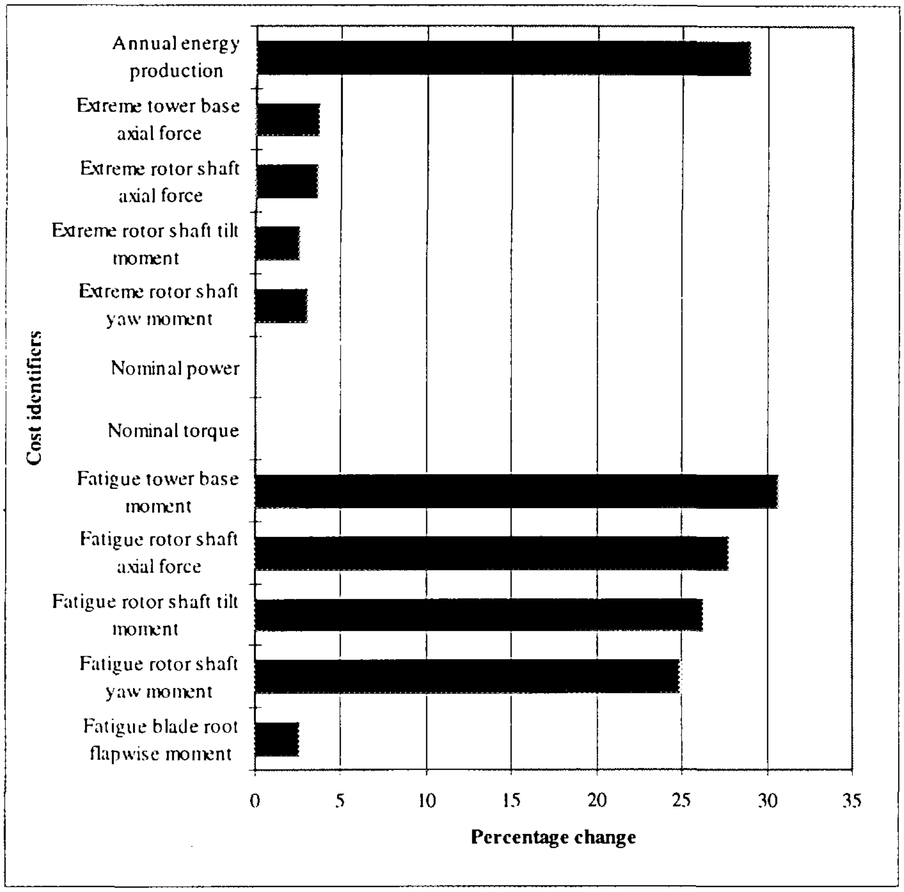

Figure 4-1 Increase in the cost identifiers for the reference wind turbine in the 5D/5D off-shore wind farm relative to the reference wind turbine at the on-shore stand-alone site.

The comparison of design loads shows that the extreme loads for the 5D/5D off-shore site were only slightly increased compared with the stand alone on-shore site, Figure 4-1. This increase was due to a minor decrease in surface roughness, resulting in a higher extreme wind speed. Except for the blade root flapwise moment, the fatigue loads were significantly increased for the 5D/5D off-shore site because of higher turbulence from operation in wake. Because of the high Wöhler curve exponent, m = 10, the blade root flapwise moment was primarily determined by the large load ranges that appear in the response time series at high wind speeds with yaw error. The time spend at this load case was very small compared with the normal operation load cases, but more than 95% of the fatigue damage occurred at large yaw error load cases for both sites. Rotor and tower loads with m = 5 were on the other hand primarily determined from normal operation and was evenly divided at low and high wind speeds.

At the 5D/5D site, there was a potential improvement of the annual production of 28% without a significant increase of the blade loads. However, the fatigue loads on other important main components such as tower and nacelle were significantly increased and this would be reflected in the cost function and in cost of energy.

Table 4-2 shows main results for the reference rotor installed on-shore and at the 5D/5D site. At the 5D/5D off-shore site, the cost function is increased by 45%. This was mainly because of the difference in the relative cost distribution, where the installation of an off-shore wind turbine was 42% more expensive than a corresponding on-shore wind turbine because of increased costs from foundation and grid connection. The remaining difference from 42% to 45% was because of the increase in loads. Even though the fatigue loads were significantly increased, this is only marginally seen on the cost function.

The increase in annual energy production on 28% for the 5D/5D site did not counterbalance the increase in the cost function on 45% and the cost of energy was increased by 13% to 0.31 DKr/kWh for the reference wind turbine at the 5D/5D off-shore wind farm.

Table 4-2 The reference wind turbine at the stand alone on-shore site compared with the reference rotor at the 5D/5D off-shore site.

	Reference: Stand alone on-shore site	Reference: 5D/5D off-shore site
Energy prod. (%)	-	28
Cost function (%)	-	45
Cost reduction (%)	-	-13
Cost of energy (DKr/kWh)	0.27	0.31

4.2 Optimum off-shore wind turbine

A wind turbine was optimized for the stand alone on-shore site and for the 5D/5D off-shore site. Table 4-3 shows main results. The main results are shown in percentage difference compared with the reference wind turbine at the actual site. Hence column 2 in Table 4-3 is shown relative to column 1 in Table 4-2 and column 3 in Table 4-3 is shown relative to column 2 in Table 4-2.

Table 4-3 Optimized wind turbines for stand alone on-shore wind turbine and 5D/5D off-shore wind farm compared with reference wind turbine on-shore and off-shore

	Reference: on-shore stand alone/ off-shore wind farm 5D/5D	Optimized: stand alone on-shore wind turbine	Optimized: 5D/5D off-shore wind farm
Design variables:			
Hub height (m)	59.5	61.1	50.2
Rotor diameter (m)	60.0	65.7	71.1
Rotor speed (rpm)	19.2	18.7	17.0
Rated power (MW)	1.50	2.00	2.00
Tip speed (m/s)	60.3	64.4	63.3
Main results:		**Relative to reference w.t. on-shore**	**Relative to reference w.t. off-shore**
Energy prod. (%)	-	21	28
Costs function (%)	-	17	16
Cost reduction (%)	-	3.3	11
Cost of energy (DKr/kWh)	0.27/0.31	0.26	0.28

For the on-shore wind turbine, the optimization resulted in a cost reduction of 3.3%. The annual energy production was increased by 21% and this was followed by an increase in the cost function of 17%. The increase in annual energy production was achieved by increasing the swept area and the rated power at the expense of the rotor speed. The tip speed was increased even though the rotor speed was reduced and this helped to maintain maximum aerodynamic efficiency at a suitable wind speed. The hub height was slightly increased.

The increase in swept area involved more expensive rotor blades because of increased loading on the blade sections. In addition, the loading on the rotor affected the costs of tower and foundation. The increase in rated power and the reduction of rotational speed increased the costs of the generator and the gear box because of a higher torque. The decrease in rotor speed helped to limit the rated power. The gain in annual energy production by a further increase in swept area could not counterbalance the increase in the cost function.

The optimization of the wind turbine for the 5D/5D off-shore site showed a cost reduction of 11%. This result was obtained by an increase in the annual energy production of 28% whereas the cost function increased 16%. Again the swept area and the rated power was increased. Rotational speed and hub height were reduced.

For the optimized wind turbine at the 5D/5D off-shore site, a cost reduction of 11% was achieved from 0.31 DKr/kW to 0.28 DKr/kW. Compared with the stand alone on-shore optimization result on 3.3%, the off-shore optimization result was promising. The result may be explained by the difference in wind climate and the difference in cost function between on-shore and off-shore. This is used by the optimization algorithm to result in different overall wind turbine designs where the reduction of the hub height for the off-shore optimization is important.

Lower hub height implies lower costs of tower and foundation but also lower annual energy production. However, because of the lower surface roughness the vertical wind gradient is less and the annual energy production was only marginally reduced. At the same time, the increased loads made tower and foundation relatively more expensive and it became more beneficial to lower the hub height. The reduction in annual energy production stemming from the reduction in hub height was counterbalanced by a reduction in tower and foundation costs.

For the on-shore stand alone wind turbine the cost of the wind turbine itself was 83% of the total cost function. For the 5D/5D off-shore wind turbine, the wind turbine cost reduced to 59% of the cost function because of the high foundation and grid connection costs. An increase in wind turbine costs at the off-shore site was therefore relatively less important for the total cost function and it therefore became feasible to increase the swept area significantly.

For both the on-shore and off-shore optimizations, the rotor diameter was increased at the expense of lower rotational speed. Tip speed was slightly increased. Because of the constraint on rated power to below 2.0 MW, an increase in swept area was more beneficial than an increase in the rotational speed. By the present selection of design variables, the specific loading of the rotor ended around 500 W/m^2 for the off-shore optimization and 590 W/m^2 for the on-shore optimization. Optimization of the blade shapes would reduce the specific loading, since more slender blades would allow the swept area to be increased even more.

In addition to the blade shape, further cost reductions should result from: More design variables, new airfoils, stronger materials allowing higher stresses and strains or more advanced power control.

The cost distribution for the optimized 5D/5D off-shore wind turbine is compared with the cost distribution for the reference rotor in Figure 4-2. Except for transport, assembly, grid connection and controller that are independent of the cost identifiers, all main component costs have increased. The main gear and generator costs were increased because of the increase in torque from higher rated power and reduced rotational speed. The increase in swept area added to the cost of the rotor blades but also to the cost of the tower and the foundation. Whereas rotor blade and tower costs were increased, the foundation costs ended at approximately the same level because of the reduction in hub height.

The reported reductions in cost of energy are biased from leaving out maintenance and other on-going costs. These are likely to be higher off-shore than on-shore. Assuming that the off-shore maintenance costs are 25% of the annual pay-back from manufacture and installation the cost reduction would be reduced to 7%.

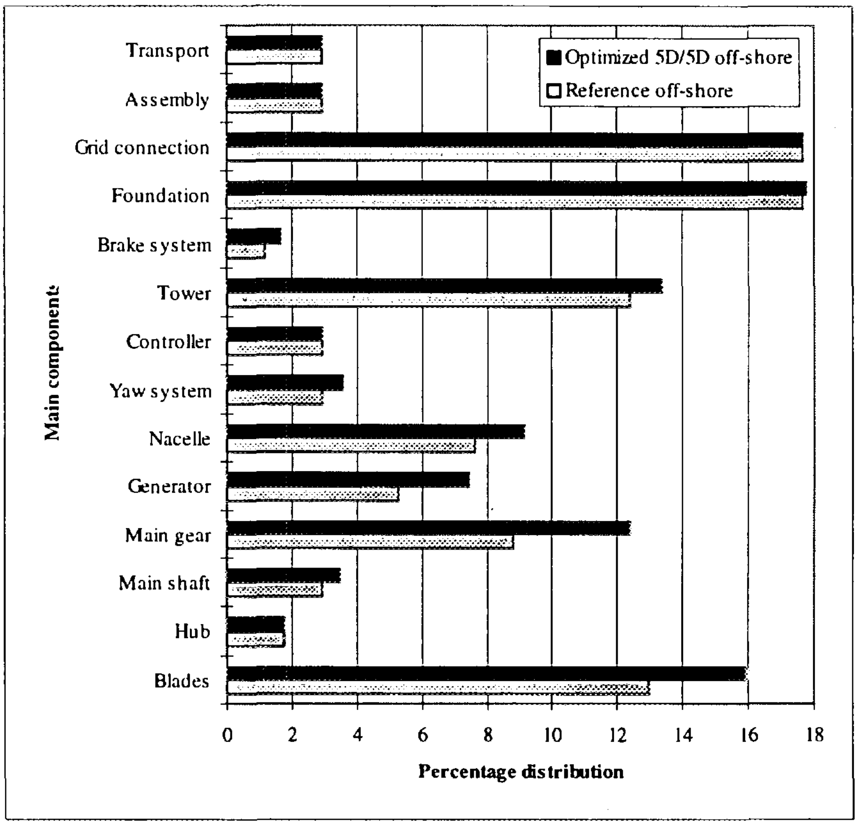

Figure 4-2 Relative cost for main components for optimized 5D/5D off-shore wind turbine compared with the reference wind turbine at the 5D/5D off-shore site.

4.3 Sensitivity analysis

A sensitivity analysis was carried out to investigate the importance of the included design variables and to find the influence on the optimization results for some of the economic assumptions and for the design loads.

Table 4-4 shows optimizations at different fixed hub heights compared with the optimum hub height. The hub height was fixed whereas the remaining design variables were optimized. When the hub height was reduced, the rated power increased together with the swept area. The rotational speed was increased until the limit on the rated power was achieved. After this, the rotational speed was reduced to limit rated power. The cost reduction varied between 5.8% and 11%.

Table 4-5 shows optimizations at different rotor diameters compared with the optimum rotor diameter. The rotational speed was reduced when the swept area was increased to limit rated power. The cost reduction varied between 5.8% and 11%.

Table 4-6 shows optimizations at different rotor speeds compared with the optimum rotor speed. The swept area was increased when the rotor speed was reduced. At low rotor speed the swept area needed to be increased to maintain high rated power. However, this increased the cost function because of increases in loads. At high rotor speeds, the swept area had to be reduced to limit rated power. However, this decreased annual production. The optimum was in between and was very sensitive to the rotor speed. The cost reduction varied between -0.6% and 11%.

Table 4-7 shows optimizations at different rated powers compared with the optimum rated power. The swept area was increased when the rated power was increased and rated power was adjusted by the rotor speed. The cost reduction varied between 1.8% and 11%.

The sensitivity of the cost of energy to variations in the design variables was summarized in Figure 4-3. The difference in cost reduction was within -0.6% to 12% for variations up to 30% in the value of the design variables.

The sensitivity of cost of energy to swept area was significant and in all cases of reduced cost of energy, the swept area was increased. The sensitivity to rated power was also significant since the swept area can hardly be increased without increasing rated power. This could only be done by reducing rotational speed, but cost was reduced more by increasing rated power. The variation with rotational speed was large and the upper limit on the rated power often determined the allowable rotor speed. The sensitivity to hub height was minor and it appeared that the hub height should be further reduced. However, the vertical wind profile becomes non-linear towards the surface which will slightly increase fatigue loads. Furthermore the clearance between the blades and the surface becomes a lower constraints.

The sensitivity study of the overall design variables indicated that a further cost reduction could be achieved by a further increase in rated power and swept area. The rotor speed would be used to adjust rated power and tower height would be kept low.

Table 4-4 Results for optimizations at different hub heights.

	Reference: off-shore	Optimized	Optimized H = 55	Optimized: H = 60 m
Design variables:				
Hub height (m)	59.5	50.2	55	60.0
Rotor diameter (m)	60.0	71.1	67.0	70.2
Rotor speed (rpm)	19.2	17.0	18.3	16.0
Rated power (MW)	1.50	2.00	2.00	1.87
Main results:				
Energy prod. (%)	-	28	23	21
Cost function (%)	-	16	13	15
Cost reduction (%)	-	11	8.8	5.8
Cost of energy (DKr/kWh)	0.31	0.28	0.28	0.29

Table 4-5 Results for optimizations at different rotor diameters.

	Reference: off-shore	Optimized: R = 60 m	Optimized: R = 65 m	Optimized
Design variables:				
Hub height (m)	59.5	58.3	58.2	50.2
Rotor diameter (m)	60.0	60.0	65.0	71.1
Rotor speed (rpm)	19.2	20.8	19.0	17.0
Rated power (MW)	1.50	2.00	2.00	2.00
Main results:				
Energy prod. (%)	-	11	20	28
Cost function (%)	-	4.9	11	16
Cost reduction (%)	-	6.0	8.4	11
Cost of energy (DKr/kWh)	0.31	0.29	0.29	0.28

Table 4-6 Results for optimizations at different rotor speed

	Reference: off-shore	Optimized: O = 15 rpm	Optimized	Optimized: O = 23 rpm
Design variables:				
Hub height (m)	59.5	59.1	50.2	60.0
Rotor diameter (m)	60.0	75	71.1	60.0
Rotor speed (rpm)	19.2	15	17.0	23.0
Rated power (MW)	1.50	1.93	2.00	2.00
Main results:				
Energy prod. (%)	-	33	28	4.2
Cost function (%)	-	31	16	4.9
Cost reduction (%)	-	1.5	11	-0.6
Cost of energy (DKr/kWh)	0.31	0.30	0.28	0.31

Table 4-7 Results for optimizations at different rated power.

	Reference: off-shore	Optimized: P_{NOM} = 1.5 MW	Optimized: P_{NOM} = 1.75 MW	Optimized
Design variables:				
Hub height (m)	59.5	46.0	53.3	50.2
Rotor diameter (m)	60.0	67.2	68.8	71.1
Rotor speed (rpm)	19.2	16.6	16.9	17.0
Rated power (MW)	1.50	1.50	1.75	2.00
Main results:				
Energy prod. (%)	-	6.3	19	28
Cost function (%)	-	4.4	12	16
Cost reduction (%)	-	1.8	6.0	11
Cost of energy (DKr/kWh)	0.31	0.30	0.29	0.28

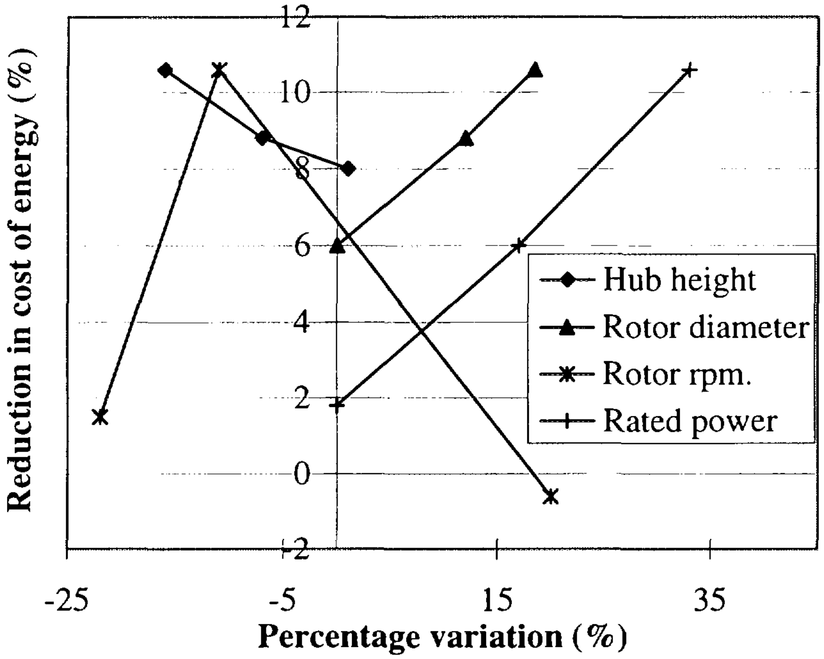

Figure 4-3 Variation in reduction of cost of energy with changes in the design variables.

Table 4-8 shows a comparison between the 5D/5D optimization from section 4.2 with fixed blade shape and an optimization with the blade chord and twist distributions included as design variables. However, the airfoils were not changed and the relative thickness distribution was kept fixed for structural reasons.

The hub height ended on approximately the same value for both optimizations. Since the cost of energy is not very sensitive to the hub height this is of less importance. The rotor diameter was increased to the upper limit when the blade shape was included in the optimization. Lower solidity allowed increased swept area. The rotor speed was reduced to limit rated power.

To obtain high aerodynamic efficiency at low wind speeds above maximum aerodynamic efficiency, the low solidity should be combined with higher rotor speed. This was not possible for the optimization result because of the limit on rated power. However, high aerodynamic efficiency is not necessarily associated with low cost of energy. In this case, the increase in swept area was more beneficial to reduction in cost of energy compared with increased aerodynamic efficiency.

By inclusion of the blade shape in the optimization, cost was reduced by 13% compared with 11% for the overall optimization. Annual energy production was increased, whereas the cost function was nearly unchanged. The cost reduction was comparable with previous results, Fuglsang and Madsen, 1996. The relevance of a new blade design increases with larger swept areas since the overall rotor solidity should correspond to the swept area so that the aerodynamic efficiency is not reduced too much. The overall blade shape in itself does not contain possibilities for significant cost of energy reductions but combined with new airfoils and eventually advanced power control reductions might be achievable.

Table 4-8 Results for optimizations with fixed/free blade design.

	Reference: off-shore	Optimized LM 29.2 blade	Optimized New blade
Design variables:			
Hub height (m)	59.5	50.2	50.6
Rotor diameter (m)	60.0	71.1	74.0
Rotor speed (rpm)	19.2	17.0	17.2
Rated power (MW)	1.50	2.00	2.00
Main results:			
Energy prod. (%)	-	28	32
Cost function (%)	-	16	16
Cost reduction (%)	-	11	13
Cost of energy (DKr/kWh)	0.31	0.28	0.26

Table 4-9 shows the cost of energy for the 5D/5D off-shore optimization at different interest rates. The optimum cost reduction does not depend on the annuity factor, so the calculation interest rate did not influence the overall design variables for the optimum rotor. However, together with the life-time, the interest rate determined the cost of energy through the annuity factor that is used to convert the optimum ratio of annual energy production to cost function into cost reduction and reduction of cost of energy.

When the interest rate was changed from 4% p.a. to 6% p.a., the cost of energy varied from 0.25 to 0.30.

Table 4-9 Cost of energy for the 5D/5D optimization at different interest rates.

	Reference: off-shore	Optimized: r = 4% p.a.	Optimized r = 5% p.a.	Optimized r = 6% p.a.
Cost of energy (DKr/kWh)	0.31	0.25	0.28	0.30

Table 4-10 shows main results for an optimization that was carried out with a change in safety class for fatigue and extreme loads to a lower class. Such a change could be relevant at off-shore sites. It means that fatigue and extreme loads were hereby allowed to increase with 11%. The rotor diameter increased by 32% and the cost of the main components was in general reduced.

The cost reduction was 14%. This indicates that development of stronger materials or reduction of partial coefficients due to a lower probability of human risks to failure are possible contributors to a further reduction in cost of energy.

Table 4-10 Results for optimizations at different safety class for fatigue and extreme loads.

	Reference: off-shore	Optimized	Optimized for reduced safety class
Design variables:			
Hub height (m)	59.5	50.2	52.8
Rotor diameter (m)	60.0	71.1	73.5
Rotor speed (rpm)	19.2	17.0	16.4
Rated power (MW)	1.50	2.00	2.00
Main results:			
Energy prod. (%)	-	28	32
Cost function (%)	-	16	15
Cost reduction (%)	-	11	14
Cost of energy (Dkr/kWh)	0.31	0.28	0.26

Table 4-11 shows main results for an additional optimization that was carried out without the load case containing large yaw errors at high wind speed. This load case causes most of the fatigue damage of the blades and an optimization without this load case would have lower blade fatigue loads.

The design variables were slightly changed, however, the cost reduction remained nearly unchanged. It could be concluded that the fatigue loads were only a part of parameters involved in the determination of cost of energy and a reduction in fatigue in itself was not very important to cost of energy, since the extreme loads at stand still then determined the main part of the cost function. However, a reduction in both fatigue and extreme loads would be reflected on cost of energy.

Table 4-11 Results for optimizations with and without extreme yaw error loads contribution to fatigue.

	Reference: off-shore	Optimized	Optimized no extreme yaw error fatigue
Design variables:			
Hub height (m)	59.5	50.2	49.4
Rotor diameter (m)	60.0	71.1	73.8
Rotor speed (rpm)	19.2	17.0	16.3
Rated power (MW)	1.50	2.00	2.00
Main results:			
Energy prod. (%)	-	28	32
Cost function (%)	-	16	19
Cost reduction (%)	-	11	11
Cost of energy (DKr/kWh)	0.309	0.28	0.27

4.4 Final optimization

A final optimization was carried out for the 5D/14D off-shore wind farm corresponding to the optimization in section 4.2 with the overall design variables. Table 4-12 shows the main results.

The final 5D/14D optimization reduced cost by 12% so that cost of energy was 0.27 DKr/kW, which was lower than the reference wind turbine at the on-shore stand alone site. Compared with the 5D/5D optimization, swept area was further increased whereas hub height and rotor speed were further reduced.

The optimum value of the design variables depended on the spacing in the wind farm, however, the overall tendencies were identical with increased swept area and reduced tower height. The cost reduction was on the same level for the 5D/5D as for the 5D/14D configurations.

Table 4-12 Results for final optimization for 5D/14D wind farm compared with 5D/5D wind farm and reference off-shore.

	Reference: off-shore	Optimized stand alone on-shore	Optimized 5D/5D off-shore	Optimized 5D/14D off-shore
Design variables:				
Hub height (m)	59.5	62.3	50.2	48.4
Rotor diameter (m)	60.0	73.2	71.1	74.0
Rotor speed (rpm)	19.2	16.5	17.0	16.2
Rated power (MW)	1.50	2.00	2.00	2.00
Main results:				
Energy prod. (%)	-	35	28	32
cost function (%)	-	33	16	18
Cost reduction (%)	-	2.0	11	12
Cost of energy (DKr/kWh)	0.31	0.27	0.28	0.27

Extreme loads and nominal loads were identical for the two sites. However, the fatigue loads differed and they are shown in Figure 4-4 for the reference rotor. Most equivalent fatigue loads for the 5D/14D site were reduced by more than 50% compared with the 5D/5D site. The blade root flapwise moment was even lower than for the on-shore site. However, the determination of this was uncertain, since it was determined mainly from low cycle fatigue with large load ranges.

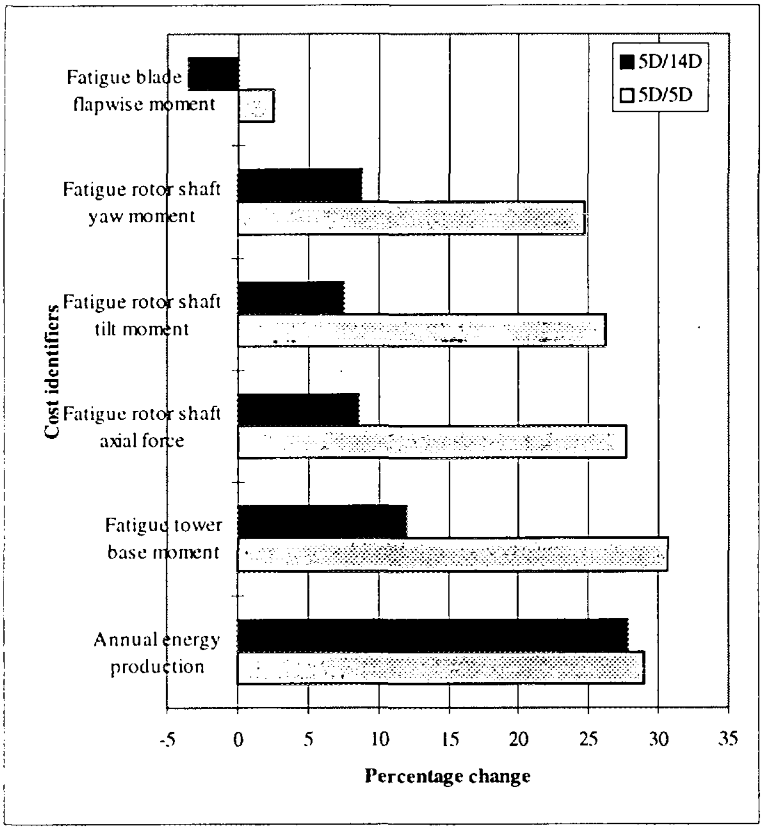

Figure 4-4 Fatigue loads and annual energy production for the reference wind turbine at the 5D/5D off-shore and 5D/14D off-shore sites shown relative to the on-shore site.

5 Conclusions

This report contains a preliminary investigation of site specific design of wind turbines for off-shore wind farm applications. The results were based on a design tool for wind turbines that involve numerical optimization and aeroelastic calculations of response, Fuglsang and Thomsen, 1998. Optimizations were carried out to find the optimum overall wind turbine design for minimum cost of energy.

Two different wind farm layouts were considered:
1. A simplified 5D/5D layout with spacing of turbines of 5 rotor diameters (5D) and spacing between rows on 5D.
2. The preliminary 5D/14D wind farm layout to be used at Rødsand has spacing between turbines: 5D and spacing between rows: 14D.

Both wind farm layouts were compared with a traditional on-shore stand-alone site.

A comparison of the design loads for the on-shore site and the 5D/5D off-shore site showed that at the off-shore site, there was a potential improvement of the annual production of 28% without a significant increase of the blade loads. However, the fatigue loads on other important main components such as the tower and nacelle were significantly increased and this would be reflected on the cost function and on cost of energy. The increase in annual energy production did not counterbalance the increase in the cost function and cost of energy was increased by 13% to 0.31 DKr/kWh for the reference wind turbine at the 5D/5D off-shore wind farm.

For the optimized wind turbine at the 5D/5D off-shore site, a cost reduction of 11% was achieved from 0.31 DKr/kW to 0.28 DKr/kW. Compared with the stand alone on-shore optimization result on 3.3%, the off-shore optimization result was promising. The result may be explained by the difference in wind climate and the difference in cost function between on-shore and off-shore. This is used by the optimization algorithm to result in different overall wind turbine designs where the reduction of the hub height for the off-shore optimization is important. The calculation of cost of energy did not include on-going costs from maintenance and this would reduce the obtained cost reduction.

For both the on-shore and off-shore optimizations, the rotor diameter was increased at the expense of lower rotational speed. Tip-speed was slightly increased. Because of the constraint on rated power to below 2.0 MW, an increase in swept area was more beneficial than an increase in the rotational speed. By the present selection of design variables, the specific rotor loading ended around 500 W/m^2 for the off-shore optimization and 590 W/m^2 for the on-shore optimization. Optimization of the blade shapes would reduce the specific loading, since more slender blades would allow the swept area to be increased even more.

The sensitivity study of the overall design variables indicated that a further reduction of cost of energy could be achieved by a further increase in rated power and swept area. The rotor speed would be used to adjust rated power and tower height would be kept low.

By inclusion of the blade shape in the optimization, cost was reduced by 13% compared with 11% for the overall optimization. Annual energy production was increased, whereas the cost function was nearly unchanged. The cost reduction was comparable with previous results, Fuglsang and Madsen, 1996. The relevance of a new blade design increases with larger swept areas since the overall rotor solidity should correspond to the swept area so that the aerodynamic efficiency is not reduced too much. The overall blade shape in itself does not contain possibilities for significant cost of energy reductions but combined with new airfoils and eventually advanced power control reductions might be achievable.

Cost of energy was estimated for the optimized wind turbine at the 5D/5D site at different interest rates. The interest rate does not influence the optimum wind turbine design, but the cost of energy varied from 0.25 to 0.30 when the interest rate was changed from 4% p.a. to 6% p.a.

An optimization was performed with a reduced safety class for fatigue and extreme loads. The reduction in cost was 14%. This indicates that development of stronger materials or reduction of partial coefficients due to a lower probability of human risks to failure are possible contributors to a further cost reduction.

The final 5D/14D optimization reduced cost by 12% so that cost of energy was 0.270 DKr/kW, which was lower than the reference wind turbine at the on-shore site. Compared with the 5D/5D optimization, swept area was further increased whereas hub height and rotor speed were further reduced.

The optimum value of the design variables depended on the spacing in the wind farm, however, the overall tendencies were identical with increased swept area and reduced tower height. The cost reduction was on the same level for the 5D/5D and for the 5D/14D configurations.

In summary we found two important results for off-shore wind turbines:

- A wind turbine for an off-shore wind farm should be different compared with a stand-alone on-shore wind turbine. The overall design changes were increased swept area and increased rated power combined with reduced rotor speed and reduced tower height.
- Cost of energy for on-shore wind turbines could not be reduced significantly in the performed optimizations, but the cost reduction for the final 5D/14D off-shore wind turbine was 12% from 0.31 DKr/kWh to 0.27 DKr/kWh. This makes off-shore wind farms competitive since the cost of energy for an off-shore wind farm becomes comparable to the reference on-shore stand-alone wind turbine. Furthermore the fatigue loads on a wind turbine in an on-shore wind farm will increase compared with the stand-alone reference, and due to this the cost of energy for on-shore wind farms will increase in favor of off-shore wind farms.

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Abstract (max. 2000 characters)

This report contains a preliminary investigation of site specific design of off-shore wind turbines for a large off-shore wind farm project at Rødsand that is currently being proposed by ELKRAFT/SEAS. The results were found using a design tool for wind turbines that involve numerical optimization and aeroelastic calculations of response. The wind climate was modeled in detail and a cost function was used to estimate costs from manufacture and installation. Cost of energy is higher for off-shore installations. A comparison of an off-shore wind farm site with a typical stand alone on-shore site showed an increase of the annual production of 28% due to the difference in wind climate. Extreme loads and blade fatigue loads were nearly identical, however, fatigue loads on other main components increased significantly. Optimizations were carried out to find the optimum overall off-shore wind turbine design. A wind turbine for the off-shore wind farm should be different compared with a stand-alone on-shore wind turbine. The overall design changed were increased swept area and rated power combined with reduced rotor speed and tower height. Cost was reduced by 12% for the final 5D/14D off-shore wind turbine from 0.306 DKr/kWh to 0.270 DKr/kWh. These figures include capital costs from manufacture and installation but not on-going costs from maintenance. These results make off-shore wind farms more competitive and comparable to the reference on-shore stand-alone wind turbine. A corresponding reduction of cost of energy could not be found for the stand alone on-shore wind turbine. Furthermore the fatigue loads on wind turbines in on-shore wind farms will increase and cost of energy will increase in favor of off-shore wind farms.

Descriptors INIS/EDB

COST BENEFIT ANALYSIS; FATIGUE; MAINTENANCE; NUMERICAL SOLUTION; OFFSHORE SITES; OPTIMIZATION; WIND LOADS; WIND TURBINE ARRAYS

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